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SECOND RESEARCH PROGRESS AND FORECAST REPORT

Image Understanding by Adaptive Networks

of Goal Seeking Neurons

AFOSR-83-0207

Principal Investigator: D. N. Spinelli

During the period 5/1/84-11/24/84 our work has progressed along the following lines.

TECHNICAL

The SUN workstation was finally delivered at the beginning of the summer. Because of several problems with the black-white and color video boards it required about two weeks to bring it fully on-line. After that we implemented the following facilities:

1) We interfaced a two-dimensional (2-D) digitizing tablet to one of the serial ports and wrote suitable programs to allow digitization and inputting of brain sections to the computer and disk. Each brain was stained with horseradish peroxidase (HRP) and consisted of about 150 sections. That is a considerable amount of data. We also wrote programs to allow the computer to generate three-dimensional reconstructions of each brain (3-D). The SUN workstation has a software facility called SUNCORE which is an extension of SIGGRAPH. This software package now allows us to view brains reconstructed in 3-D from any point of view and perspective. That is, on the color monitor we can rotate, translate, and scale on any of the x, y, z axes the reconstructed brain in minutes. These different transformations would require months for each one if done by hand. Different colors are used to signify different brain structures, cell markers, and projection pathways which have been stained by the HRP injected at the site where we have recorded from adapted

cells. At some future time we plan to also automate the inputting of 2-D sections by using a TV camera to view the sections directly (this is dependent on hardware availability and better image analysis programs than we now have).

These newly acquired capabilities are extremely important to us because they allow us to evidence cortical and subcortical regions that feed information to the areas we analyze with microelectrodes to study the functional responses of single neurons. At this writing we have reconstructed three brains. Now that most of the initial preparatory work is done we expect to be able to process a brain every three weeks.

A first impression gained from these three brains is that numerous cortical areas send terminals to a recording site; that is, there seem to be substantive interconnections between somato-sensory, Claire-Bishop, insular, and visual 1, 2, 3. We have not done any recordings or HRP injections in the insular cortex areas 18 and 19. All our recordings were from somato-sensory, area 17, and Claire-Bishop in the cortex. Subcortically we recorded only from the hypothalamus. In all these regions we found adaptation to varying degrees.

2) Single-cell recording with microelectrodes is a highly precise method yielding high quality data, but it is very slow, time-consuming, and ill-suited for prospecting in brain regions which might be essential to image understanding, but are not known to be so. We felt the need for a method that would allow a reasonably fast determination of adaptation in a given area. Further, we wanted to be able to measure time delays between regions to determine the direction of information flow. We also wanted to be able to follow only neural activity related to our task, that is, related to adaptation. To this end we implemented a computer program that does the following: a) alternates flashes of horizontal bars (E1) and vertical bars

(E2) in the left eye (E1 and E2 are equated for number of bars and brightness and fall on the same patch of retina), b) digitizes neural activity during the presentation, and c) generates separate event histograms for E1 and E2 (HE1 and HE2, respectively). If there is no adaptation HE1 and HE2 should have the same amplitude because the percentage of cells responding to E1 is the same as that responding to E2. On the other hand, if adaptation has taken place and the left eye received E1, thne the amplitude of HE1 should be larger as more cells will respond to E1. Opposite considerations apply to the right eye which has received training to E2.

We tested the program using semimicroelectrodes in area 17 and in Claire-Bishop where we showed that adaptation took place. The program worked very well. It should be pointed out that we consider "unequivocal adaptation" to be present only when we can demonstrate cells that respond to E1 and E2 (the reason for this criterion is that this type of response is not found for cells in cats that have not been trained in our procedure). By this very strict criterion a positive result does not prove adaptation, but simply that the area investigated has been modified by experience and is worth the time and effort of single cell analysis. The program allows time measurements and promises to be very valuable on both fronts.

EXPERIMENTAL

We have worked at three areas: anatomy, neurophysiology, and a number of informal psychophysical experiments.

1) The anatomical work had the overall purpose of producing the block diagram of the architecture of the system under investigation. Our procedure consisted of injecting one microliter of a 25% solution of HRP into a cortical area, i.e., Claire-Bishop, at the end of a recording session during which,

using microelectrodes, we analyzed the response properties of single cells to bars of different orientation. We waited 24 hours to give the enzyme time to undergo retrograde transport and then sectioned and stained the brain using an improved chromophore we developed. Brain sections were then inputted into the SUN workstation for 3-D reconstruction as described above.

2) One or our tasks was the determination of the optimum time separation between E1 and E2 yielding the strongest adaptation. To this end kittens were trained at different E1-E2 alternation rates. To obtain additional evidence as to the time dimension we recorded from the visual cortex the electrical potentials generated by flashing E1 in one eye followed at different intervals by E2 in the other. The rationale for this relatively simple experiment was that the largest interaction between E1 and E2 should take place at the optimum time for adaptation. The maximum interaction was found to take place at 400 milliseconds, plus or minus 50. While this result was expected and hoped for, especially because of our single cell recordings, it leaves a number of questions open (see THEORY section). Principally, we are concerned that there might be more than one peak in the function.

3) We have been testing and tuning the prospector program on cortical areas that we have shown to contain cells that have adapted to E1 and E2 as described above. As already stated, the program is performing very well. We expect to be using it to explore regions of the cortex which are known to receive information from visual and nonvisual regions of the brain, that is polysensory cortex. Structures to be investigated include the hippocampus and the cerebellum. These structures have been shown to be involved in the learning of eye blink responses by several investigators and are worth looking into. At this time we don't expect to go into any deep analysis of them as we believe that other structures which are involved in reward and motivation,

i.e., the hypothalamus or the reticular formation (we have some data showing HRP pickup in these structures) are more relevant to image understanding.

4) During a discussion of heterostatic theory with Harry Klopf we had predicted that simply alternating E1 and E2 between the two eyes with a rate of 400 msecs should lead to adaptation because heterostatic theory predicts adaptation if E2 follows E1 at approximately 400 msecs and causes depolarization. We did this experiment and the prediction was confirmed (see in the THEORY section that modern learning theory would have predicted the same results on a somewhat different rationale). The experiment led to a serendipitous, but extremely interesting observation. We noticed in several of our recordings that a large disproportion of cells were tuned to E1, the horizontal bars. This was puzzling because each stimulus was supposed to act as the reinforcer of the previous one. Careful measurements of E1-E2 timing revealed that E1 and E2 each lasted exactly 400 msec, as programmed; however, because some counters had to be reset in the program, after E2 presentation, switchover time between E2 and E1 was about 20 msecs longer. The results show how critical time relationships are in determining adaptation. In this case it seems that this slight difference makes E2 more reinforcing to E1 than E1 is to E2. We are now training some kittens to alternations of 300 and 500 milliseconds to determine the slope of the adaptation curve. Hopefully we are close to the peak (see, however, the THEORY section on this).

5) We have become convinced that, given the appropriate training parameters, we should be able to demonstrate large adaptive phenomena and structural rearrangements in <u>adult</u> cats. This would be an extremely important result, because showing that visual receptive field shapes can be modified to reflect the nature of the experience would bring us to the doorsteps of the engram and would have important practical implications, e.g., in the training

of pilots or education in general. Accordingly, we have begun training a small group of adult cats. Positive results in this experiment would also enable us to substantively shorten the time required for each experiment.

6) As a result of another discussion with Harry Klopf we decided that it would be profitable to invest a small amount of time to carry out a few observations on the perceptual concomitants resulting from viewing the stimuli we use with our cats. The purpose of this, again, was to obtain a subjective impression of what happens when E1 and E2 alternate between the two eyes at different rates of alternation. One immediately obvious result was the observation (by the Principal Investigator) that flicker fusion was absent at rates of 100/sec or more. Normally flicker fusion occurs at rates of 30-50/sec (e.g., the image of a television set does not flicker and the frame rate is about 60/sec). Increase in this rate could be interpreted as an increase in information processing capability in the visual path achieved by this very simple method. Further, very compelling attentional phenomena occurred at different frequencies of alternation, possibly indicating that E1 and E2, when interleaved in this fashion, acted indeed not only as stimuli but also as reinforcers. Further, best durations for E1 and E2 seemed to be spread out from about .1 to 3 seconds with a possible peak at about .5 seconds. As this experiment seemed to engage eye dominance and/or binocular rivalry mechanisms, the Principal Investigator viewed some of the images in Gregory's book The Intelligent Eye and measured the rate of alternation in dominance to be about once every 4 seconds. This is surprisingly close to the 8 second delay which yields best learning in some forms of conditioning (see Figure 15 in Contemporary Animal Learning Theory by A. Dickinson).

THEORY

We feel that we have made considerable progress on this front in the face of extremely complicated issues. What we have been attempting to do is to relate our neurophysiological findings with heterostatic theory and with modern learning theory. (For a very good, short and clearly written book on the subject see Contemporary Animal Learning Theory by A. Dickinson). We have some very striking results, neurophysiologically, showing that the brain machinery responsible for image understanding is extremely plastic and adaptive (in certain conditions). We have been attempting to a) understand what rules are operative, b) the neural circuitry at work, and c) as we consider these phenomena correlates of learning, to develop a theory that takes into account current thinking on this subject. We feel that we are very close to accomplishing some of these goals. First, it should be said that even though heterostatic theory takes off from Skinnerian principles by almost literally equating a nerve cell with a rat in a Skinner box, the theory is primarily addressed at small nets of goal-seeking components (neurons in our case). That is, the theory is hardware oriented. In fact, one of our goals is to better understand the brain's hardware and possibly to apply this knowledge to new computer architectures. It is remarkable how this relatively simple and at times counterintuitive theory has been able to predict two of our best demonstrations of adaptation: 1) that cells with simultaneous tuning for E1 and E2 would be produced by a simple avoidance training (see Plasticity, the Mirror of Experience), and 2) the present results in which adaptation is demonstrated after simply alternating E1 and E2 between the two eyes without a global reinforcer. Heterostatic theory makes these predictions based on the time relationships between E1 and E2 and activity traces in pre- and postsynaptic structures and their time relationships. The direction of

adaptation, i.e., the strengthening or weakening of synapses, would be determined by depolarization or hyperpolarization. In fact, the theory is primarily concerned with neural events locally and avoids any involvement with the nature of E1 and E2. On the other hand, contemporary learning theory has little to say (not for lack of trying) about neuronal events and concentrates on the cognitive aspects of learning with special reference to associative learning and the relationships between E1 and E2.

Possibly the most popular theory at present, because it explains the largest number of many complex experiments, is the one proposed by Rescorla-Wagner. Essentially, this theory concentrates on E2 and states that E2 has to be surprising; that is, E2 must be unpredicted by E1 for associative learning to take place. After E1 and E2 become associated no further learning takes place. The Rescorla-Wagner theory would predict the alternation result we have demonstrated for the following reasons: a) it falls in the class of sensory preconditioning. That is, initially E2 is unpredicted (surprising) by E1; therefore, associative learning starts and continues until E1 predicts E2. As E1 and E2 alternate similar considerations apply to E1. b) Presenting E1 and E2 as we do, that is with goggles, minimizes contextual overshadowing, at least in the visual domain, which facilitates learning. c) The task has some of the properties that produce <u>superconditioning</u>. This is because if one eye sees E1 then the prediction is that the other eye should see E1 also (for animals with frontally located eyes). This makes E2 <u>more surprising</u> than no prediction at all (see Rescorla on superconditioning). There remain many unclear issues, two of which seem to be foremost. One is time: from the point of view of heterostatic theory there should be only one optimum time between E1 and E2 because a neuron "sees" only excitation, inhibition, and its own firing activity. With a few additions, such as hormones, diffuse potentials,

etc., this is of course true. Contemporary learning theory, on the other hand, envisages different systems obeying the same rules, but with different time constants, because experimentally different optimum times have been reported, ranging from .4 seconds for eye blink to 7-8 seconds for lick suppression and heart rate change. There seems to be an effect due to the quality of E1 and E2 and an interaction between them for which no theory that we have come across seems to have a ready explanation. This problem is discussed by Dickinson. The fact that the spontaneous rhythm of alternation in eye dominance seems to be about 4 seconds could be an indication that optimum delay is far longer than we suspected, or that there is more than one peak in the function. After all ambliopia ex anopsia, that is the loss of binocularity in some children is a massive, if maladaptive, phenomenon of plastiicty due to binocular rivalry; thus the spontaneous alternation of dominance could be very close to the optimum timing. It remains a mystery why the visual system is not completely prewired both in terms of binocularity and in terms of feature primitives; however, this very plasticity indicates that without it the vision system might not work! That makes it even more imperative that we understand what brings it about and the rules and circuitry that are its foundations.

The other problem has to do with the nature of E2: E2 has to be surprising or unpredicted by E1. These two expressions are used interchangeably by Dickinson. Actually we prefer surprising in its common meaning, which is different from unpredicted. There are myriad events which are unpredicted and we know from subjective experience that rarely they induce any learning. Surprising events however are remembered. A surprising event generates an orienting reaction which is not necessarily, in fact rarely, present to the innumerable unpredicted events that befall us. To be

surprising an event needs to be not only unpredicted, but of interest. Again, this has to do with the nature of the information represented by E2 (and/or E1?), a thorny problem only hinted at in learning theory and apparently irrelevant to heterostatic theory but which, in my opinion, needs to be addressed. While I have no formal answer at the moment it seems, at a first approximation (these comments apply only to vision), that adaptation should be greater the greater the difference between E1 and E2, provided that E1 is transformable into E2. Intuitively it could be said that when there is no difference between E1 and E2 then E1 predicts itself and no learning is necessary or desirable. If E1 is not transformable into E2 then the two events should not be linked, at least perceptually. If there are any merits to this line of reasoning the consequences are far reaching because it would mean that adaptation, i.e., what the vision system stores, includes the transformation rules and not just the images themselves. This is very different from the kind of analysis most investigators think image understanding requires and would give quite a different meaning to much data.

WORK TO BE PERFORMED: THIRD YEAR

1) Neurophysiology: Using the prospector program we plan to construct a precise functional block diagram of the structures functionally involved in our training procedure and to measure time delays to identify information flow. Cellular recordings will be critical in that they allow identification of signature cells, i.e., cells that respond both to E1 and E2. These response properties are not found in cats not trained with our procedure. Strength of adaptation in groups trained at different time intervals (measured in terms of number of signature cells found and response selectivity) will enable us to plot best delays for maximum adaptation.

2) Anatomy: We will continue 3-D reconstructoins of brains to show and chart a structural block diagram of brain areas that have adapted to the task and relate it to the functional one.

3) We will do a small number of experiments in adult animals. If, by using the behavioral task we have developed which involves superconditioning, we can produce adaptation comparable to the one we have demonstrated in kittens, including receptive fields maps that look like the visual stimuli used, we will have attained a fundamental result.

4) We will integrate, as far as possible, our physiological, behavioral, and anatomical findings with what is known in the literature with the aim of generating a viable theory of image understanding. By viable theory we mean a theory precise enough to be suitable for computer simulation.